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EXECUTIVE SUMMARY

STUDY OF SPIN-SCAN IMAGING FOR OUTER PLANETS MISSIONS

Contract No. NAS2-7096

For - National Aeronautics and Space Administration
OAST Systems Studies Division
Ames Research Center
Moffett Field, California

By - Santa Barbara Research Center and
Lunar and Planetary Laboratory/University of Arizona

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CONTENTS

ILLUSTRATIONS

TABLES

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Section 1
INTRODUCTION

1.1 PRIOR HISTORY OF SPIN-SCAN IMAGING

The first spin-scan imagers were the Spin-Scan Cloud Camera (single color) and the Multicolor Spin-Scan Cloud Camera (three colors) launched on ATS-I and ATS-III, respectively. (The single-color instrument failed in 1972 after more than five years of operation, while the three-color instrument is still operating six years after launch.) The spin-scan Imaging Photopolarimeter (IPP) instruments on Pioneer 10 and 11 are designed to take two-color imagery during the Jovian encounters. In addition to the imaging function, the IPP instruments are being used in a faint-light mode to take sky maps in both radiance and polarization and will be used in the photopolarimetry mode during the Jovian encounter to record the radiance and polarization of Jupiter. The Visible-IR Spin-Scan Radiometer (VISSR) is a multispectral instrument that will operate in both visible and infrared wavelengths. The VISSR will be launched in early 1974 and will operate on the Synchronous Meteorological Satellite (SMS).

It has been argued that the complex geometry entailed by many possible space missions would preclude the use of the spin-scan imaging approach. With modern-day computing facilities this is clearly not the case. In practice, the Pioneer 10 and 11 flyby missions, with the spin-scan IPP providing the imaging capability, are a severe departure from the ATS-I and -III spin-scan imagers used in synchronous orbit. While the Pioneer flyby geometry is indeed complex, the problems of image reconstruction have been solved, and the resultant software is extremely flexible. Thus, while the IPP flown on Pioneer 10 and 11 is a point scanner (single field of view), the software has been modified to accommodate multiple detectors, variable stepping rates, etc.

Diverse requirements, such as for orbiter and polar flyby missions, also are readily accommodated, and these are discussed in the Technical Report.

1.2 BASIC CONCEPTS

The two fundamental types of spacecraft imaging instruments are scanning imagers and frame imagers. Scanning instruments are further subdivided into those flown on three-axis stabilized spacecraft and those on spin-stabilized spacecraft; instruments in the last category are referred to as spin-scan imagers. The fundamental nature of spin-scan instruments implies some basic advantages over the other two types of imagers.

With spin-scan imaging the angular rotation produced by a spinning spacecraft is used to provide one of the two relative angular motions required to scan a scene. As a consequence of the spacecraft roll, no physical motion of the imager in the roll (clock) angle direction is required, although it is often desirable that the angular sampling interval be electronically selectable. Scan motion in the orthogonal (cone angle) direction is normally required in a spin-scan imager unless either a single-swath image is sufficient or relative motion between the imager and scene provides the required scanning.

While the roll of a spinning spacecraft is essential for the operation of a spin-scan imager, it can often necessitate the use of elaborate image motion compensation with a frame imager. Finally, where the available telemetry rate is limited, the use of extensive, on-board memory storage or a very slow scan readout would be required for a frame camera. This latter approach can be particularly unattractive where operation in a high energy radiation environment is required. In contrast, a spin-scan imager can readily be designed to match the available telemetry rate, with the on-board storage requirements being limited to that for data collected during one roll of the spacecraft.

A spin-scan imager with proper design can be considered to be a high resolution radiometer which utilizes the spacecraft roll to provide a portion of the scanning motion. This is a particularly attractive choice when high radiometric quality as opposed to cosmetic quality imaging is desired. This is true since high radiometric accuracy is more easily achievable with a spin-scan imager than with a frame imager. While the Multispectral Scanner (MSS) flown on the Earth Resources Technology Satellite (ERTS) is not a spin-scan imager, it is a scanning radiometer designed to compete directly with framing cameras. Return-beam-vidicon (RBV) cameras, one for each of three spectral bands, are also flown on the ERTS. The radiometric quality of the MSS imagery is certainly superior to that achievable with the RBV cameras, even with extensive calibration corrections. The shading across the image is the most serious contributor to the lower radiometric accuracy capability of such a frame camera. The geometric precision of the RBV imagery is probably somewhat better than that of the MSS, although the MSS imagery is now being used routinely for cartography, indicating the increased confidence of cartographers in these data. The spectral band-to-band registration of the MSS data is much better than one pixel for the MSS and better than that achievable with the three RBV cameras.

Where desirable to operate in several spectral bands and over a wide spectral range, the flexibility possible with an all-reflective spin-scan imager (radiometer) is especially significant. The Visible-IR Spin-Scan Radiometer (VISSR) is representative of these characteristics. Even for multispectral operation over the limited spectral range (for simultaneous imaging), the typical framing camera utilizes separate telescopes and cameras for each spectral band.

1.3 SCOPE AND RESULTS OF STUDY

The areas considered to be within the scope of this study are indicated in Table 1-1. These areas are discussed in detail in the Final Technical Report for this study. However, to assist the reader in obtaining an overview, the scope and methodology are reviewed in the next section.

In Table 1-2, the study results are summarized along with the major recommendations for future effort towards development of a versatile spin-scan imager for outer planets missions. It should be stressed that the major problem has not been to find a spin-scan imaging system that can meet the anticipated scientific requirements and be compatible with the expected mission and spacecraft constraints, but to determine which of the several feasible systems should be selected as the optimum choice. The results and recommendations are also reviewed in the next section.

Table 1-1. Scope of Spin-Scan Imaging Study

IMAGER CONSTRAINTS
SCIENTIFIC
SPACECRAFT-IMPOSED
ENVIRONMENTAL
IMAGER COMPONENT STUDY
DETECTORS
SCAN MECHANISMS
OPTICS
IMAGER SYSTEM MODELING
RESOLUTION (MTF, SAMPLING)
SCENE CHARACTERISTICS
SIGNAL-TO-NOISE RATIO MODELING
INCLUSION OF CONSTRAINTS
PRELIMINARY DESIGNS
IMAGER POINT DESIGNS
DETAIL PROMISING POINT DESIGNS
PARAMETERIZE IMPORTANT CHARACTERISTICS
OPTIMIZE ITERATED POINT DESIGNS
IMAGING SEQUENCE PLAN
JUPITER ORBITER IMAGING
SATELLITE IMAGING
IMAGING AT OTHER OUTER PLANETS
IMAGE PROCESSING
ALTERNATIVE METHODS
RECOMMENDED METHOD
SAMPLE IMAGERY

Table 1-2. Summary of Study Results

SPIN SCAN IMAGING MODELING SYSTEMATIZED
THREE DISTINCT POINT DESIGNS SHOWN SUITABLE TO PROVIDE:
1. 10 km RESOLUTION AT JUPITER
2. RADIOMETRIC QUALITY IMAGERY
3. FULL DISK IMAGES AT $10R_J$ (< 50 kbps)
4. INSTRUMENT WEIGHT < 10 kg
IMAGE SEQUENCING TECHNIQUES DEVELOPED
SOLUTION OF SPIN SCAN GEOMETRY PROBLEM GIVEN
RECOMMENDATIONS
1. MODIFY AND QUALIFY DIGICON
2. RADIATION-TEST CANDIDATE DETECTORS
3. MONITOR CCD DEVELOPMENTS
4. MONITOR IPP SOFTWARE DEVELOPMENTS

Section 2
SUMMARY OF STUDY EFFORT AND RESULTS

2.1 SCOPE OF STUDY FOR SPIN-SCAN IMAGING FOR OUTER PLANETS MISSIONS

The areas included in this study are indicated in Table 1-1.

The constraints that must be imposed on the Outer Planets Missions (OPM) Imager design are obviously of critical importance and include those imposed by the desired scientific return, the spacecraft limitations, the operating environment, and the technological limitations. The imager-system modeling formed an important part of this study. In the system modeling analysis, the important parameters are defined and a systematic means for trade-off analysis is developed and applied to a specific Jupiter orbiter mission.

Three promising point designs are detailed for values of the system variables established in the system modeling, and the important physical characteristics for each point design are parameterized. The engineering-type inputs so developed then permit point-design optimization.

Possible image-sequence plans for a Jupiter orbiter mission are discussed in detail. The discussion applies to a particular series of orbits that allow repeated near encounters with three of the Jovian satellites although the approach can be readily extended to the development of image-sequence plans for other missions.

The data handling involved in the image processing is discussed, and it shown that only minimal processing would be required for the majority of the images for a Jupiter orbiter mission. Where a small amount of distortion is present, a simple picture-point-assignment program sufficient to rectify the images is described. For those few images subject to a significant amount of distortion, the more general methods developed to rectify the image data generated by the Pioneer 10 and 11 IPP instruments would be required and are outlined.

2.2 SYSTEM MODELING METHODOLOGY

A general system modeling methodology has been developed during the course of this study for analyzing spin-scan imaging systems. The process is an iterative one in which the mission, scene, spacecraft, and component characteristics, coupled with the scientific requirements, serve to determine the initial point-design values through the system modeling figure. The system modeling trade-off figure generated for each basic point design is used to vary such important system parameters as instantaneous field of view, telescope diameter, spectral bandwidth, and signal-to-noise ratio (SNR).

The initial point-design values determined may be further modified in a detailed point design by additional spacecraft constraints (e.g., maximum memory read-in rate) and operational considerations (e.g., minimization of command activity) not included in the trade-off figure. From the detailed point design the important instrument characteristics are parameterized, e.g., the dependence of weight on telescope diameter and number of imager channels. The suitable combination of the system modeling figure with the parameterized point-design data permits the optimization of the point-design subject, e.g., to minimize instrument weight. When this procedure is followed for each point design under consideration, it is then possible to compare several point designs optimized on a consistent basis.

In Figure 2-1, a flow outline for systematically evaluating a particular imager point design as described above is given. The first step of the system modeling is to model the SNR over the possible range of scene and instrument parameters that may be encountered. The detector choice primarily determines the parametric form of the

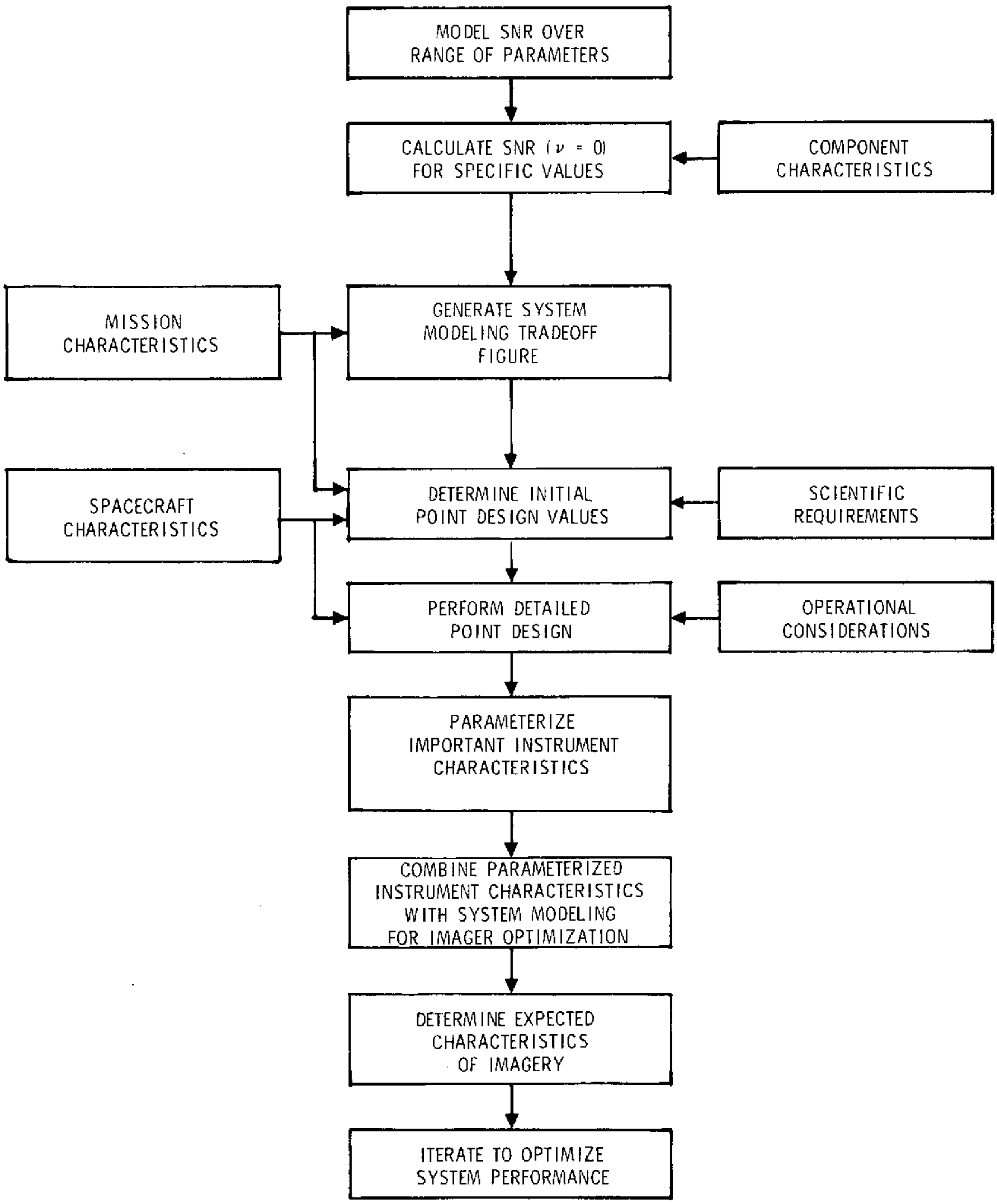

Figure 2-1. Outline of System Modeling Methodology

equations which relate the SNR to the other variables of the instrument. This is discussed in detail in Sections 5 and 6 of the Technical Report. The SNR at zero spatial frequency [SNR (ν = 0)] is next calculated in several spectral intervals across the useful range of the detector for a specific scene condition and for specific instrument characteristics.

The system modeling figure can be generated from the calculated SNR (ν = 0) and the scaling law for the instantaneous field of view (IFOV), the spacecraft roll rate, and the telescope diameter for the selected spectral intervals. Also introduced into the figure are the surface resolution as a function of range and the underlap constraint. The flyby or orbital characteristics lead to the underlap constraint, which determines the minimum number of detectors for a given roll rate.

From the system modeling figure, initial point-design values are determined consistent with the scientific requirements and the mission and spacecraft constraints. The scientific requirements would include the specification of the IFOV (or equivalent surface resolution at given distance), SNR (ν = 0), number and size of images, number of gray levels, allowable aliasing, etc. The spacecraft characteristics limit the range of such variables as roll rate, wobble angle, telemetry rate, and memory read-in rate. The mission and spacecraft characterstics interact to produce limits on the thermal and high-energy radiation environments of the instrument. They can thereby restrict the point design.

A detailed engineering analysis of the initial point design leads to refinement of the initial point design so as to satisfy the science requirements and be compatible with the mission and spacecraft characteristics. Such operational considerations as suitable command functions for the imager also affect the detailed point design. From the engineering analyses the important instrument characteristics are parameterized. This could include such items as weight as a function of the telescope diameter and the number of channels, and power as a function of the number of channels.

In the case of an OPM Imager, it is apparent for Pioneer-class spacecraft and the known characteristics of spin-scan imagers that the minimization of instrument weight for a given performance is of overriding importance. Hence, by combining the system modeling figure with plots of weight versus telescope diameter and number of channels, the weight can be optimized (minimized) subject to specified values for the SNR and IFOV. For the OPM Imager Point Designs this resulted in curves of weight versus spacecraft roll rate (or equivalently, versus number of detectors, since rpm is proportional to the number of detectors if other variables are constant). The minima of such curves for each OPM Imager Point Design thereby yield the optimum design points. It is then possible to compare the OPM Imager Point Designs on a consistent basis, knowing that each has been independently optimized.

The interaction of bit rate, roll rate, sampling rate, number of detectors per spectral band, number of spectral bands, number of gray levels, samples per pixel, data compaction factors, and line length can be combined to yield a telemetry-rate modeling figure. This serves as a simple means to see the effect on the imagery as various instrument and spacecraft parameters are changed. The implied requirement on the spacecraft memory capacity follows from the results of such an analysis.

2.3 OPTIMIZED DESIGNS OF OPM IMAGER FOR JUPITER ORBITER MISSION

The primary constraints applicable to the optimization of specific OPM Imager Point Designs are sufficient resolution and signal-to-noise ratio, no underlap or significant aliasing, and operation within the possible spacecraft roll-rate range. The iterative process of optimization through the system modeling figure and parametric curves of the important instrument properties resulted in the point design performance characteristics shown in Table 2-1. Each point design was optimized individually subject to the constraint that weight was to be minimized. Implicit in the designs are assumptions regarding basic design philosophy. In general, high reliability, radiation resistance, and operational flexibility were emphasized.

Table 2-1. Comparison of OPM Imager Point Designs Optimized for Minimum Weight

POINT DESIGN	TELESCOPE DIAMETER (cm)	NUMBER OF DETECTORS	ROLL RATE (rpm)	WEIGHT (kg)
DESIGN 1 (DIGICON-TYPE DETECTOR)	15	32	5	8.2
DESIGN 2 (GaAs PHOTO-MULTIPLIERS)	16	12	13	9.5
DESIGN 3 (SILICON PHOTO-DIODE ARRAY)	14	18	9	7.3

(WEIGHT MINIMIZED FOR SNR (ν = 0) = 100 AND IFOV = 0.1 mr)

THESE POINT DESIGNS PROVIDE:

1. 10 km RESOLUTION AT JUPITER
2. RADIOMETRIC QUALITY IMAGERY
3. FULL DISK IMAGES AT $10R_J$ (<50 kbps)
4. INSTRUMENT WEIGHT ~ 9 kg

Based on the results of this study, Point Design 1 is the preferred design. The primary reason for this is the predicted superior radiation resistance of this design relative to the other designs. The point designs that employ photoemissive detectors (Designs 1 and 2) have the advantage that the signal-to-noise ratio would decrease only as the square root of a decrease of scene flux on the detector, e.g., due to a lower scene radiance or a narrower spectral bandwidth. In contrast the signal-to-noise decrease with silicon array detectors (Design 3) would be directly proportional to a decrease in the scene flux on the detector (thermal or preamplifier noise limit assumed). The weight differences between the three designs are fairly small and the slight advantage indicated for Design 3 results since it has the lowest detector assembly weight. The simpler telescope drive system possible with Point Design 1 somewhat reduces this weight advantage relative to Design 1.

For both Designs 1 and 3 an increase in the number of channels could be accommodated with a very small increase in the detector assembly weight. (The main weight increase would be due to the additional electronics required.) However, since the available spacecraft telemetry rate fixes the number of bits that can be transmitted per roll, increasing the number of channels beyond the minimum required due to underlap considerations normally would not be desirable. This follows since fewer channels would reduce shading effects (responsivity variations across the array), simplify calibration, allow less costly optics, and permit lower read-in rates for data into the spacecraft memory (at a fixed roll rate).

2.4 IMAGE SEQUENCING PLANS AND PROCESSING

Possible image sequence plans were prepared for a specific Jupiter orbiter mission that allows repeated near encounters with the three Jovian satellites, Io, Europa, and Ganymede. The image sequence plans were developed to be compatible with the characteristics of the OPM Imager Point Designs that were optimized for Jupiter. While the detailed sequencing developed is for a specific set of orbital characteristics, the general method can be readily extended to other missions.

Various methods of image processing are discussed in the Technical Report with the view towards simplification of the data handling. It is shown that only minimal processing would be required for the majority of the images obtained during the example Jupiter orbiter mission. A simple picture-point-assignment program is described which is suitable to rectify images with a small amount of distortion. For images taken near periapsis and subject to a significant amount of distortion, software similar to those developed for the Pioneers 10 and 11 encounters would be required. These more general methods which require additional computer processing time are outlined for completeness in the Technical Report.

2.5 RECOMMENDATIONS FOR FUTURE EFFORT

Four major recommendations seem appropriate based on the results of this study:

1. Modify and qualify a Digicon-type detector for spaceflight use.
2. Thoroughly radiation test both a Digicon-type detector and silicon solid-state array detectors including CCD arrays.
3. Closely monitor future CCD developments.
4. Similarly monitor ongoing Pioneer Imaging Photopolarimeter (IPP) software developments.

Other areas of importance that would benefit from additional work include:

1. Trade-off analysis relating to the selection of an optimal data compaction method with emphasis on outer planets missions imaging applications.
2. Selection of optimum sampling properties for an Outer Planets Mission Imager.
3. Application of the system modeling methodology to other types of missions, e.g., to cometary encounters.

Finally, it seems appropriate as regards the spacecraft to:

1. Study ways to increase the available telemetry rate since the quantity of the imagery is clearly bit rate dependent.
2. Evaluate possible means to reduce the wobble angle and improve roll reference repeatability should even greater resolution later be required.